Dual Balloon Concept For Lifting Payloads From The Surface Of Venus

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Two high-rated Venus mission concepts proposed in the National Science Foundation Decadal Survey require a balloon to lift payloads from Venusian surface to high altitudes: Venus Surface Sample Return (VESSR) and Venus In-Situ Explorer (VISE). In case of VESSR the payload is a canister with the surface sample plus a Venus ascent vehicle (VAV), which is a rocket that takes the sample into orbit for rendezvous with an Earth return vehicle. VISE is envisioned as a more limited precursor mission where the surface sample is only taken to high altitudes so that non time-critical analyses can be performed. From the balloon point of view, the only difference between these two missions is that the VESSR payload to be lifted is very much larger than VISE because of the inclusion of the VAV.

A key problem is that at the time the decadal survey was published (and now), no high temperature balloon technology existed to implement either mission. Prior technology development efforts had concentrated on a single balloon that could operate across the entire 0-60 km altitude range, tolerating both the sulfuric acid aerosols and the extreme temperatures of -10 to +460 °C. However, this problem was unsolved because no combination of sufficiently lightweight balloon material and manufacturing (seaming) technology was ever found to tolerate the high temperatures at the surface. The authors describe a solution to the problem based on the idea of using a two-balloon approach. One balloon is optimized for high temperature service in the lower atmosphere, while the second is optimized for high altitude performance. Both balloons can be made from available materials with known fabrication technology. The near-surface balloon will be a metal bellows made of stainless steel or other suitable alloy. The relatively high mass of metal material is allowable in this architecture because only small balloons are needed to lift significant payloads in the dense lower atmosphere of Venus. The second, high-altitude balloon will be made of a more conventional Teflon-coated Kapton film. This much lighter material enables the large balloon volumes needed for expansion in the low density upper atmosphere while the Teflon coating simultaneously provides sulfuric acid protection throughout the ascent.

In operation, the metal bellows balloon will be inflated with either helium or hydrogen gas during the initial descent and landing of the overall vehicle. During the descent and the short stay on the surface, the second, high altitude balloon remains in a thermally insulated container along with the vehicle avionics and other sensitive components. Once the sample has been collected, the payload and the two balloons will be released from the lander and begin to ascend. At a crossover altitude of approximately 12 km, the temperature will be low enough (~370 C) to deploy the high-altitude balloon from its insulated container. The valve that connects the two balloons will then be opened to allow the buoyancy gas from the metal bellows balloon to transfer to the high altitude balloon. The metal bellows balloon will be released once this gas transfer is complete, and the remaining vehicle will ascend to its floating altitude of approximately 60 km while the bellow will float at much lower altitude. Detailed calculations have been performed to design the two balloon vehicle and quantify its performance during all phases of the mission. The paper includes key results from these trade studies for balloon sizing and mass, crossover altitude, and payload temperature.

Nomenclature

A	=	finesse ratio
HAB	=	high-altitude balloon
LAB	=	low-altitude balloon
D	=	diameter of balloon
σ	=	areal density

C_d	=	drag coefficient
d_{ins}	=	thickness of thermal insulation
ρ_{ins}	=	density of thermal insulation
PCM	=	phase-change material
ρ_{PCM}	=	density of PCM
H_{pPCM}	=	latent heat
T_{melt}	=	melting temperature
C_{PCM}	=	specific heat capacity
d_{pcm}	=	thickness of the PCM layer
N_t	=	number of inflation tanks
Mg	=	mass of buoyant gas
M_{land}	=	mass of lander
M_{can}	=	mass of ascend canister
M_s	=	mass of flight train
W	=	vertical velocity
G	=	acceleration of gravity
B	=	buoyant force
S	=	drag area
ρ_a	=	ambient density
U	=	wind velocity
μ_a	=	mean molecular mass of atmosphere
μ_g	=	mean molecular mass of buoyant gas
V	=	volume
F_l	=	free lift

Subscripts:

k	=	HAB
b	=	bellows
IS	=	inflation system
ins	=	insulation
cont	=	container

I. Introduction

DETAILED understanding of structure and evolution of Venus though not yet realized might be the most important goal of the Solar system studies. Being a close sister of Earth in terms of size and mass, and having a thick atmosphere the Venus evolved into waterless deserted autoclave completely coated with clouds consisting from concentrated sulfuric Why, when and how did it happened, what are composition of the surface and roles of surface and surface-atmosphere interactions, what are other factors that are responsible for this evolution? These are very practical questions that has to be answered to understand and possibly prevent evolution of our Earth in the same direction.

Harsh environment (temperature 460 C, pressure 92 bars) presents a major challenge to any mission intended to study the surface of Venus. So far 8 Soviet Venera and Vega probes made first basic studies of Venus surface for 1-3 hours. This time is insufficient for detailed sample analysis. At the same time it is unlikely that probes with conventional electronics that does not tolerate high temperatures will survive much longer. These considerations drove authors of the National Research Council Decadal Survey [1] (guiding document for NASA Solar System exploration) to name two near-term Venus missions that will allow much more detailed analysis of the surface samples. One of these missions - Venus In-Situ Explorer - would conduct robotic sample analysis in the benign room temperature and pressure environment of the upper troposphere. The other mission of a flagship class – Venus Surface Return – will deliver sample for precise analysis in laboratories on Earth. Both missions require lifting of payloads from the surface to upper troposphere:55-60 km) sample canister and analyzing instruments for VISE and rocket with sample canister for VESSR. The only practical vehicle for this cargolifting is a balloon. To be able to ascend in the upper troposphere the balloon has to be made of light-weight material.

There were several studies and attempts to develop technology for the high-temperature balloons. The most advanced was JPL Venus Geoscience Aerobot study [2]. This and some others concentrated on a light-weight films that would tolerate all range of Venus temperatures and will not be affected by sulfuric acid of clouds. The most expectations were based on PBO film coated with noble metals. However in spite of some progress the technology is still very immature and it is unclear that it can be developed for the near- or even long-term missions.

At the same time there are number of available materials that can withstand somewhat lower temperatures of 350-370 C that occurs at altitudes of 12-15 km. It leads to the idea of resolving problem with a two-balloon approach: one balloon has to tolerate surface temperatures while not necessary to be light-weight, the other balloon has to operate at "moderate" temperatures of 350-370 C and be sufficiently light-weight to be able to lift payloads to the upper troposphere. Development of the dual-balloon follows in the next parts of the paper.

II. Venus Environment

We remind first of environment where the balloon system has to operate. Figure 1 shows temperature, pressure, density and windspeed profiles [3]. Important for future discussions values are: parameters near the surface (at lowlands) – density 64 kg/m3, temperature 463 C, windspeed <1.5 m/s, at 15 km – density 28 kg/m3, temperature 348 C, windspeed 16 m/s, at 60 km – density 0.47 kg/m3, temperature -10 C, windspeed 80 m/s. Carbon dioxide is the main constituent (95%); other components are nitrogen (3%), argon (<1%). The atmosphere is very dry though there is ambiguity in water abundance. All atmosphere above 12-15 km is involved in strong prograde rotation with windspeeds from 10-15 m/s at 15 km to 100 m/s at 65-70 km. Diving mechanism of this super-rotation is still a mystery. In spite of high windspeeds turbulence in bulk of the atmosphere is very weak while convection observed in the 53-55 km where two Soviet Vega balloons flew in 1985. Clouds cover all Venus. The cloud deck is near 47.5 km and clouds extend to approximately to 70 km. Clouds consist of concentrated sulfuric acid droplets in bimodal or trimodal distribution..

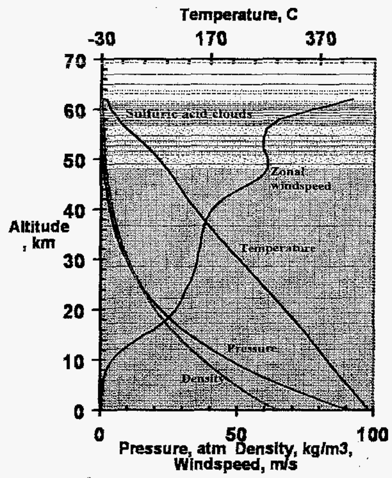

Figure 1. Vertical structure of Venus atmosphere.

III. Dual-Balloon Mission Concept

The flight system will include two balloons: one of them - low-atmosphere balloon (LAB) – will operate in low atmosphere (altitudes 0-20 km), the other – high-altitude balloon (HAB) will lift payload form 10-15 t0 55-65 km. The entry spacecraft includes lander with sampling device and sample transfer mechanisms, sample canister, ascent module, two balloons, inflation system filled with buoyant substance and appropriate containers and thermal protection system (see Figure 2). Ascend module is either pressure vessel with instruments for sample analysis, telecommunication system and other avionics or Venus Ascent Vehicle (VAV) – rocket that will be launched from the upper troposphere to return the sample canister to Earth. All systems will be installed in the aeroshell. A combination of conventional thermal insulation and phase-change material (PCM) used to protect HAB and control temperature of the inflation tanks.

Though there are could be different ideas for implementation of the LAB we selected the metal bellows as the most technologically developed. The bellows as well as the HAB will be described in more details in the next section.

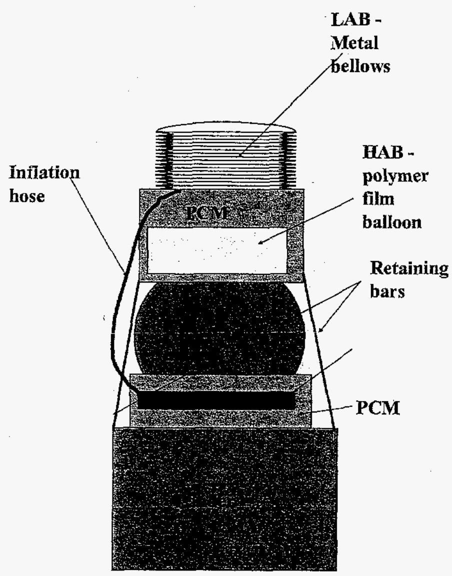

Figure 2. Schematic diagram of the probe.

All phases of the mission from launch to entry in the atmosphere are similar to other Venus probe missions and we will not cover them in any details. The lander will be discussed only in parts necessary for operation of the dual-balloon system. There are several scenarios of operations in the atmosphere. They have similarity in major parts but can differ in details. We describe one of them, which seem to be the most mass efficient.

Figure 3 shows atmospheric part of the mission. After entry in the atmosphere the entry vehicle (EV) will deploy a small pilot parachute that will be used as a stabilizer. At altitude 53-55 km (where temperature and pressure are similar to low troposphere of Earth) the pilot chute with the backshell will be separated and second small parachute will be deployed at low subsonic speed and then the aeroshell will be jettisoned.

At some moment when the probe is at altitude 10-20 km the first orifice of the inflation system will be opened and the LAB will begin to inflate. Properties of the thermal control system and sequence of opening of orifices will be designed in such a way to maintain pressure inside LAB equal to ambient pressure and to ensure that LAB volume is within elastic limit (see next section). Inflation will continue until pressure inside tanks will equalize with the ambient pressure.

Buoyant force applied to the LAB (located on top of the probe) ensures aerodynamic stability of the probe and makes possible to release the parachute during descent if terminal velocity of the probe at landing is within a safety limit of the lander.

Surface operations after landing include imaging, in situ measurements, sample acquisition and transfer of the sample to ascend canister. The canister is not necessary to be a pressure vessel. Main requirement is to isolate the sample from interaction with the atmosphere during ascend. Duration of staying on the surface is governed by thermal design of the lander and ascend vehicle and time necessary for sample acquisition and transfer.

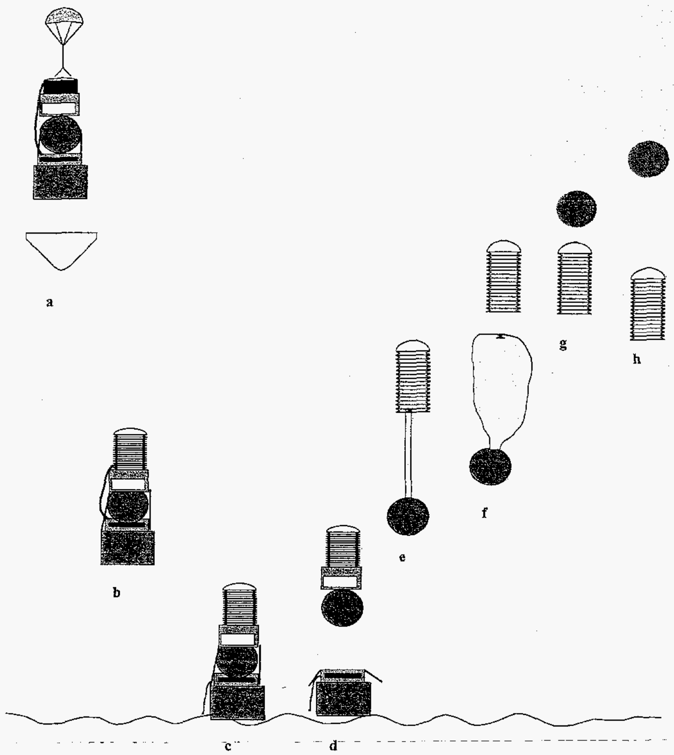

Figure 3. Probe mission profile. *a - aeroshell separation, b - LAB inflation, c – surface operations, d – launch, e – deployment of HAB, f – inflation of HAB and LAB separation, g – HAB ascent to cruise altitude, h – HAB at cruise altitude.*

After completion of the surface operations the retaining bars (Figure 2) that secure the ascend elements to the lander will be released and the flight train consisting now of the partially inflated bellows (LAB), HAB packed in the container, ascend module and the sample canister (not shown in Figure 3) will begin to ascend. Amount of gas would be designed, as at terrestrial balloon launches, to ensure the free lift equal to 15-20% of weight of the flight train. Expansion of gas during ascend to higher altitudes will increase length (and volume) of the bellows.

At the crossover altitude the bellows expands to maximum length. At this time the HAB container will be opened the HAB will be deployed. A combination of shock-absorbing devices (e.g. ripstitches) will be used to limit loads on the HAB within safety limits. The HAB container with remaining PCM will be then released that will result in increase of the ascend velocity. After a short time the valve connecting the bellows with the HAB will be opened and the expanding gas will start to fill the HAB thus allowing to maintain the buoyant force.

In this configuration the flight train continues to ascend. At an altitude where most of the gas has been transferred to the HAB while remaining gas provides positive buoyancy for the bellows alone, the other valve will close the HAB inflation port. After that the bellows will be released. The bellows and the HAB with ascend module will continue to ascend, initially the bellows moving faster than the HAB. The bellows can be equipped with a simple aerodynamic device providing a side force to move the bellows away from the ascending HAB. The windshear will provide additional horizontal separation between these two vehicles.

After that the HAB with the ascend module and sample canister proceed to ascend until at the cruising altitude the whole HAB volume will be filled with the buoyant gas while excess of the gas will be vented.

IV. Balloons

A. Low-Altitude Balloon - Metal Bellows

Earlier ideas to use metal foils for the LAB are impractical since the foils are too fragile and have no tear resistance. There are no too many ways to build balloons of thicker metals. Probably one of the most attractive would be a bellows design. Existing hydroforming technology developed by the Gardner Bellows Corp allows to build bellows from thin sheet metals with expansion ratio of 10-12 (ratio of completely inflated bellows length to packed length). The candidate materials for the LAB are stainless steel, titanium or even aluminum.

A 0.35-m diameter fabricated by the Cardner Bellows Corporation from 7-mil (0.18 mm) thick stainless steel is shown in Figure 4. The bellows has 70 convolutions and can expand inelastically 12 times from length of 0.19 m when its internal pressure is 84 mB less than ambient to 2.16 m when pressure inside exceeds ambient by >630 mB (reusable elastic length is 0.89 m). The bellows has been subjected to temperature increase to 460 C (right picture in figure 4) then inflated to full length, inspected and checked for helium leaks. No leaks have been found.

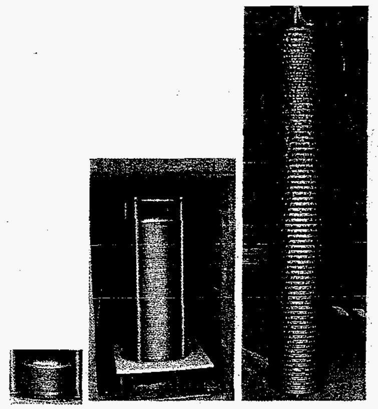

Figure 4. 0.35-m diameter metal bellows. *a – at ΔP=-84 mB, b – at ΔP=114 mB, c – at ΔP=630 mB after exposure to +460 C*

Bellows size and mass depend on payload mass (mass beneath the bellows), crossover altitude, buoyant gas, bellows material and expansion ratio. Figure 5 shows mass of helium-filled bellows as function of the payload mass for crossover altitude 15 km. It is assumed that the bellows design is similar to the prototype that we tested: the bellows is made of stainless steel with thickness 7 mil and has expansion ratio 11. In fact the expansion

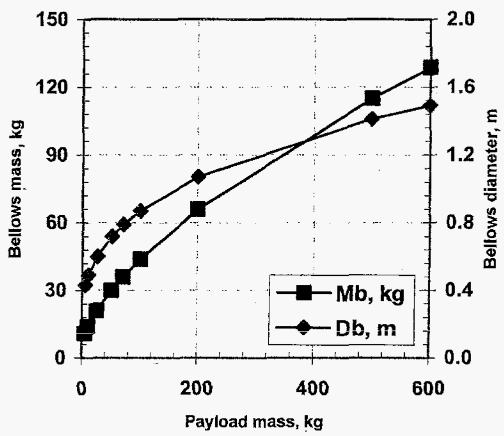

Figure 5. Bellows mass and diameter as function of the payload mass. *Crossover altitude 15 km, buoyant gas - helium*

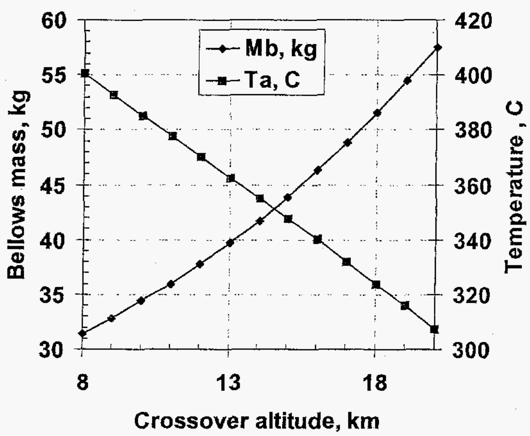

Figure 6. Bellows mass and temperature of the atmosphere as function of crossover altitude. *Payload mass 100 kg*

ratio influence on stored volume not on the bellows mass itself. Figure 5 data shows that the bellows is quite effective: ratio of the bellows mass to payload mass is less than 0.44 for payloads over 100 kg and goes down to 0.2 for 600 kg payload. It is comparable with low-altitude terrestrial balloons and is much better than the ratio for stratospheric balloons. Mass efficiency of the bellows increase also with increase of its diameter.

Bellows size and mass are dependent on the altitude where the payload has to be lifted (crossover altitude) that is illustrated in Figure 6 for bellows with the payload mass 100 kg. The bellows mass increases almost by 70% when the crossover altitudes goes from 10 to 20 km. High-temperature tolerance of the high-altitude balloon is the prime factor in selection of the crossover altitude.

B. High-Altitude Balloon

Filled volume of the main balloon increases 60 times when the balloon ascends from the cross-over altitude of 15 km to cruise altitude 60 km. The metal bellows will be impractical even if it could be built with such expansion ratio: it would be 15 m diameter, 900 m height and 70 tons mass bellows to lift 100 kg payload; this bellows would require 7000 kg of helium.

Polymer films or composites based on them are the only practical materials for the high-altitude balloon (HAB) construction. Set of main requirements for the HAB is quite challenging: (a) it has to operate from high-temperatures at crossover altitudes (300-380 C) to -10...+30C at the cruise altitude, (b) it has to operate within clouds made of 75-85% concentrated sulfuric acid at temperatures beginning from ~100 C at lower cloud deck, (c) it has to withstand a dense packing inside the entry vehicle and balloon container, (d) it has to survive shock during deployment at the crossover altitude, (e) it has to have low leak rate, additionally for superpressure balloon (f) it has to tolerate pressure loads during cruise phase.

Since a cruise duration from several hours to a day may satisfy as Venus Sample Return as Venus In-Situ Explorer type of missions, the zero-pressure balloon would be design of choice. Even for this design there is no homogeneous film that would satisfy all requirements (a)-(e). From all films variety only some fluoropolymer films like Teflon can tolerate sulfuric acid and operate in high temperatures. Teflon is main candidate for the outer layer . However, Teflon has low tensile strength, especially at high temperatures, and is highly permeable; it has to be augmented with another high-temperature film that is stronger and less permeable.

Two high-temperature films - polyimide Kapton and polybenzooxazol (PBO) films [4] – can be used for the inner layer. PBO film though being superior to Kapton is still in experimental phase of development and is currently available only in small pieces. The Kapton film is in industrial production for over 20 years and among other applications is widely used for space inflatables. Small weight loss and shrinkage when kept in helium indicate that Kapton may operate up to 500 C. Our preliminary tests showed that Kapton becomes brittle in air at 460 C and certainly does not degrade at 350-370 C. Teflon PTFE film has melting point 327 C and might be used even beyond this temperature as a coating for Kapton. Industrial Kapton FN film is a co-extruded combination of the Kapton and

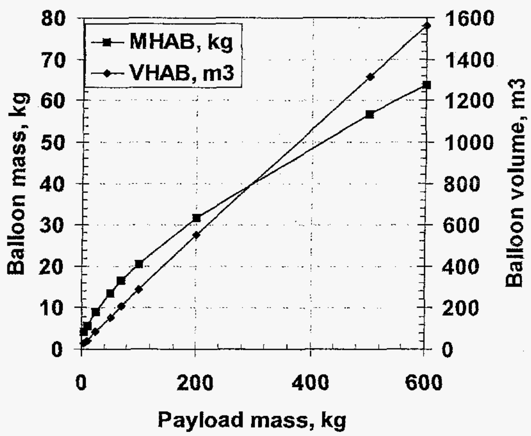

Figure 7. Mass and volume of the high-altitude balloon as function of the payload mass. *Cruise altitude 60 km, buoyant gas - helium*

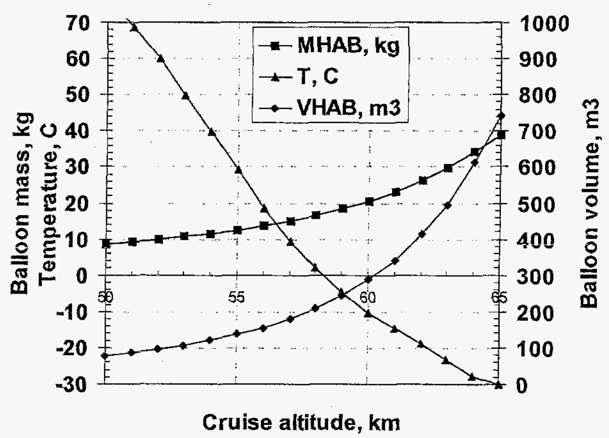

Figure 8. Mass, volume of the high altitude balloon and temperature of the atmosphere as function of cruise altitude. *Payload mass 100 kg*

Teflon FEP films that also might be used for the HAB construction. Teflon FEP has melting point 260 C.

Since the HAB will be packed and stored in thermally insulated container until deployment at the crossover altitude, the balloon film will not be exposed to high temperatures in the packed state where is a danger that melted Teflon will adhere. Probability of adhesion is much less after deployment and can be decreased further by a molybdenum oxide coating.

The zero-pressure balloon can be built in cylinder or natural shape. Actually independently of design balloon will be unfilled and have the same bubble-with-tail shape during the most time of ascent. It will be filled and take the designed shape only at the last phase of ascent. In our trade study example we assumed that the HAB is cylindrical balloon made from Kapton FN film. Balloon volume depends primarily on payload mass and cruising altitude and does not depend on the crossover altitude. Figures 7 and 8 show the HAB diameter and mass as function of the payload mass and cruising altitude. We used balloon with finesse ratio 4 and made from Kapton 150FN019 film. This film consists of 1-mil layer of the Kapton FN and 0.5-mil layer of Teflon FEP. Areal density of the material is 62.5 g/m^2.

In general, the HAB is quite mass efficient and ratio of balloon mass to payload mass decreases from 0.25 to 0.1 for payloads from 50 to 600 kg (cruise altitude 60 km). This efficiency decreases with increase of the cruise altitude. Choice of cruise altitude is dominated by mission objective and available mass. If it is VISE type where the benign environment plays a major role, than optimum cruise altitude would be in vicinity of 56 km where temperature of the atmosphere is close to room temperature while pressure is approximately 0.5 atm. For VESSR mission aerodynamic losses for VAV are dominant and cruise altitude should be as high as possible.

In our example (crossover altitude 15 km, cruise altitude 60 km) mass of the bellows exceeds mass of the HAB approximately two times in the whole range of payloads. Ratio of the bellows mass to HAB mass decreases when crossover altitude decreases (bellows becomes lighter) or the cruise altitude increases (the HAB becomes heavier). For a given payload the combined mass of LAB and HAB decreases when both crossover and cruise altitudes decrease.

V. Dual-Balloon System Model

We developed a simplified model of the dual-balloon system behavior in all phases from beginning of descent in the atmosphere to ascent to the cruise altitude. Simulated system included all elements was shown in Figure 2: lander, ascent module, metal bellows (low-altitude balloon), high-altitude balloon packed in the container filled with phase-change material, inflation tanks in their thermal protection system. The COSPAR model of Venus atmosphere for latitudes <30° [3] was used for environment description.

The LAB is characterized by the diameter D_b, expansion ratio A_b, material density ρ_b, thickness e_b and yield strength Y_b maximum reversible length L_{br} and drag coefficient C_{xb}. The cylindrical-shaped HAB is described similarly by diameter D_k, finesse ratio A_k, material areal density σ_k, drag coefficient during ascent C_{dk}, packing coefficient k_{pack} – ratio of volume balloon material to volume of the packed balloon.

The HAB container is modeled as a double-walled cubic box (Figure 9) filled with a layer of vented insulation [5] (thickness d_{ins}, density ρ_{ins}); thermal conductivity of this material was approximated by the thermal conductivity of the ambient atmosphere with a multiplier 1.5. Inside container another layer of phase-change material (PCM) surrounds the packed HAB. The PCM is characterized by density ρ_{PCM}, latent heat H_{pPCM}, melting temperature T_{melt}, heat capacity of liquid (C_{PCM}) and solid (C_{ice}) phases. Thickness of the PCM layer is d_{pcm}. The container walls have thickness d_{cont} and made of material with density ρ_{cont}. Size of the packed HAB $a_{kpk}=V_{kpk}1/3$ (V_{kpk} – volume of the packed HAB).

The inflation system consists of N_t inflation tanks each containing M_H mass of buoyant gas. Each tank has diameter D_t, length L_t and mass M_t. The tanks are enclosed in the container with isolation and PCM similar to the HAB container. Corresponding nomenclature is: the vented insulation thickness d_{insis}, density ρ_{iniss};. thickness of the PCM layer is d_{PCMis}. walls thickness d_{contis}. Dimensions of the tanks' pack are length L_{IS}, height H_{IS}, width W_{IS}. Masses of the lander and ascend capsule are M_{land} and M_{can}, maximum diameter of the system during descent is D_{des} and drag coefficient C_{des},

Vertical motion of the system during both descent and ascent simulated with a simple quasistationary model with vertical velocity calculated from the terminal velocity equation

$$W = sign(B - M_s g) * \sqrt{\frac{2(M_s g - B_s)}{C_{ds} S_s \rho_a}}$$

where M_s, B_s, C_{ds}. and S_s are mass, buoyant force, drag coefficient and drag area of the system at any current moment, g – acceleration of gravity (8.87 m/s^2), ρ_a – ambient density. Inflated volumes of LAB and HAB, volume of the pressure vessel V_{seal} as well as external

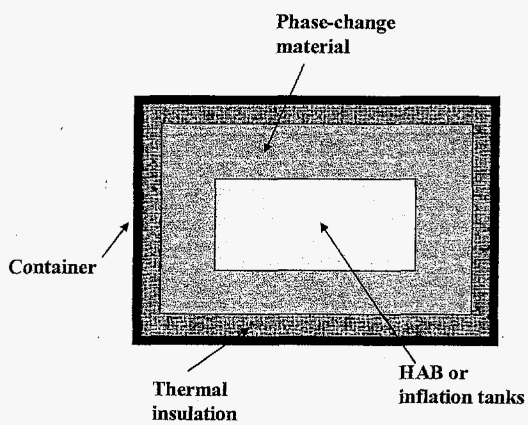

Figure 9. Thermal protection of HAB and inflation tanks

volume of the inflation tanks used to calculate the system buoyancy. Inflated volumes of LAB and HAB, volume of the pressure vessel V_{seal} as well as external volume of the inflation tanks used to calculate the system buoyancy. It is assumed that the temperature of buoyant gas inside HAB and LAB is equal to the ambient temperature.

For simplicity amount of the buoyant gas inserted into the LAB was approximated by linear law

$$M_{g\inf} = R_g(t - t_{0\inf})$$

where R_g – rate of inflation (kg/s), t_{0inf} – inflation start time.

We adjusted volume (and mass) of PCM, inflation rate and start time to complete inflation before all PCM in the inflation system enclosure be melted. Inflation begins at some point during descent and is completed before landing.

After landing, the system stays with the partially inflated bellows while PCM in the HAB container continues to melt. Surface wind is the main risk factor for balloon from the surface. Single balloon has to have great volume and length to lift payload from surface to the upper atmosphere. In presence of wind the major part of the balloon and the payload will be dragged along the surface during launch and may easily be damaged. Unlike it, the bellows in dual-balloon system will be inflated only to approximately one half its length which by itself is an order of magnitude shorter that length of a single balloon. Besides the bellows is stiff and aerodynamic drag of the wind (that is <1.5 m/s near Venus surface) will not tilt it and bellows will take vertical orientation after the launch. The system will start to ascent with flight path angle (angle between velocity and horizontal plane) equal to *arctg (W/U)*, where U is wind velocity and W is defined by (X) with system mass and buoyancy

$$M_s = M_{can} + M_b + M_g + M_k + M_{PCM} + M_{ins} + M_{cont}$$
$$Bs \approx \mu_a / \mu_g * M_g + \rho_a V_{can}$$

where μ_a and μ_g – molecular masses of the atmosphere and buoyant gas, M_g – mass of gas in bellows, V_{can} – sealed volume of the ascend payload. Compressibility of the atmospheric gas was neglected.

At the crossover altitude where the bellows extends for full length the HAB is deployed, the liquid PCM will be dropped while the HAB container with thermal insulation may still remain in the flight train. Also the valve between LAB and HAB opens and HAB stars to fill with buoyant gas. Main equations are:

$$M_s = M_{can} + M_b + M_k$$
$$M_{gb} = V_{bm}\rho_a\mu_a / \mu_g$$
$$M_{gk} = M_g - M_{gb}$$
$$F_{lb} = V_{bm}\rho_a - M_b - M_{gb}$$
$$F_{ls} = M_{gk}\mu_a / \mu_g + V_{bm}\rho_a - M_g - M_s$$
$$Vk = M_{gk}\mu_a / \mu_g / \rho_a$$
$$D_k = (6/\pi * V_k)^{1/3} \qquad (6/\pi * V_k)^{1/3} < D_{km}$$
$$D_k = D_{km} \qquad (6/\pi * V_k)^{1/3} \geq D_{km}$$
$$C_d S = \frac{\pi}{4}\max(D_b^2 C_{xb}, D_k^2 C_{xk})$$
$$W = \left(\frac{2F_{ls}g}{\rho_a C_d S}\right)^{1/2} \qquad F_{ls} > 0$$

The bellows will be released when lift of the HAB will be sufficient to further ascent while free lift of the bellows is still positive. Both vehicles – the HAB with suspended payload and bellows continue to ascend. Their vertical separation will be controlled by difference in vertical velocities, horizontal separation – by wind shear. Ascend rates are

$$W_b = \{\frac{2[V_{bm}\rho_a(h_b) - M_b - M_{gbr}]g}{\rho_a(h_b)\, C_{xb}\, (\frac{\pi}{4} D_{bm}{}^2)}\}^{1/2} \quad F_{lb} > 0$$

$$W_k = \{\frac{2[V_k\rho_a(h_k) - (M_k + M_{can} + M_{gk} + M_{cont} + M_{ins})]g}{\rho_a(h_k)\, C_{xk}\, (\frac{\pi}{4} D_k{}^2)}\}^{1/2}$$

Both HAB and bellows will ascend to their respective equilibrium cruise altitudes. They will went buoyant gas maintaining near zero superpressure.

For thermal calculations we neglected heat capacity of the inner system (HAB or inflation tanks) and assumed that its temperature is equal to temperature of PCM. PCM is initially in a solid phase, it maintains a constant temperature T_{melt} during melting. The PCM temperature rises further when all PCM is melted and than starts to boil or transit to supercritical state. The melted amount of PCM calculated as

$$\frac{dM_{PCM}}{dt} = \frac{\kappa S_{conti}}{H_{melt} d_{insi}} (T_a - T_{melt})$$

where S_{conti} and d_{insi} – surface area and isolation thickness of the appropriate container (HAB or inflation system).

Temperature of PCM in liquid phase T_{PCM} computed using differential equation

$$\frac{dT_{PCM}}{dt} = \frac{\kappa S_{cont}}{d_{ins} M_{PCM} C_{PCM}} (T_a - T_{PCM})$$

VI. Example of System Simulation

The following example presents results of simulation of the dual-balloon system sized to lift ascend canister mass of 70 kg. Such canister could serve either as for a precursor or for VISE type of mission. Mass of the lander is

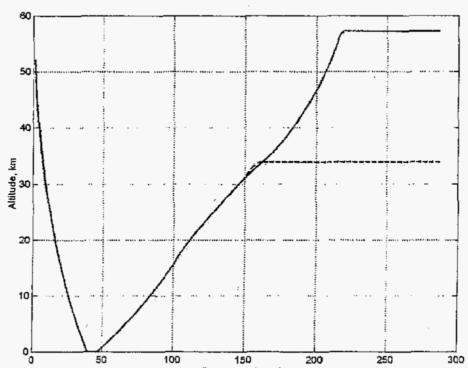

Figure 10. Altitude history. *Solid line - altitude during descent and altitude of HAB, dashed line – altitude of bellows*

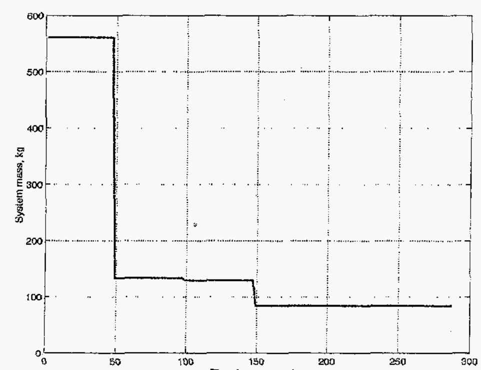

Figure 11. System mass as function of time

200 kg. We used bellows and HAB described in section IV. Hydrogen used as buoyant gas, water – as PCM. Crossover altitude is 15 km (temperature 348 C, pressure 33 bar, density 28 kg/m^3.), cruise altitude for the HAB – 58 km (temperature 2 C, pressure 0.33 bar, density 0.63 kg/m^3.).. Bellows has expansion ratio 9, diameter 0.97 m,

mass 45.1 kg, maximum expansion length 8.73 m, and maximum volume 6.45 m^3. Constructed shape of HAB is cylinder with aspect ratio 4, diameter 3.4 m, mass 8.2 kg, and inflated volume 123 m^3.

The packed HAB is cube with side 0.36 m. The layer of PCM around it –water ice/ water - has thickness 0.01 m, volume 4 l. The vented thermal insulation has thickness 0.02 m, density 150 kg/m^3, volume 18.7 l, mass 2.8 kg. The HAB container made from 1mm titanium. Mass of container is 3.6 kg.

Inflation system includes 7 tanks containing 1.2 kg hydrogen each, total mass of hydrogen 8.4 kg (we used of-the-shelve tanks as prototype). Pack of tanks has dimensions 1.52x0.65x0.76 m. The water layer around tanks has thickness 0.02 m and mass 110.2 kg. The thermal insulation and inflation system container are similar to those of the HAB, Thermal insulation mass is 18 kg, mass of container 22.2 kg.

Total system mass during descent is 561 kg, diameter 1.5 m, drag coefficient 0.7. The ascend system is launched 7 min after landing. Mass at launch from the surface is 142 kg, free lift in mass units is 43 kg.

Some results are shown in Fig.10-14. In all charts time scale is minutes from entry in the atmosphere.

The system lands on the surface of Venus in 39.5 min. By this time 5.3 kg of ice in the HAB container and 31 kg in the IS container is melted. Amount of PCM for the IS protection in this example is well in excess and can be reduced significantly. Further system mass reduction is possible if the bellows will be inflated during descent.

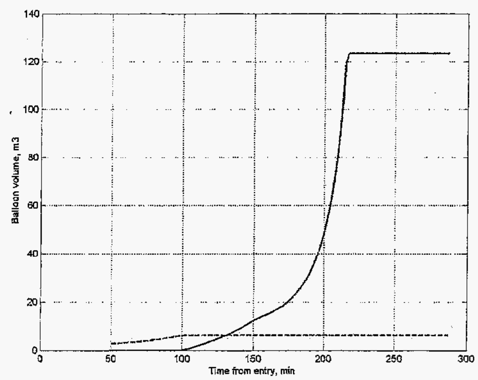

Figure 12. Inflated volume of balloons as function of time. *Solid line – volume of HAB, dashed line – volume of bellows*

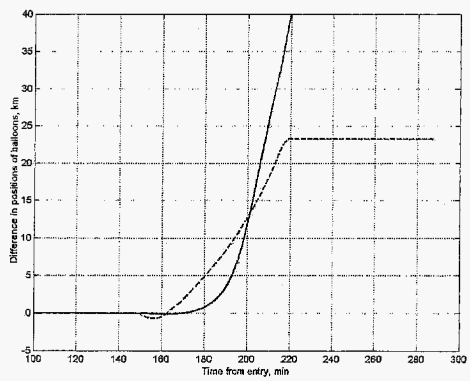

Figure 13. Horizontal and vertical separation between HAB and bellows after bellows' release. *Solid line* x_{HAB}-x_b, , *dashed line* h_{HAB}-h_b

Ascent system mass is 146.8 kg i.e. 418 kg lighter than during descent since the lander and IS remain on the surface By the time of launch from the surface (at *t*=47 min) the bellows (bellows length at this time is 333.7 m) is inflated and provides free lift 35.4 kg (24%) for the ascent flight train.. Ascent rate at launch is 4.5 m/s.

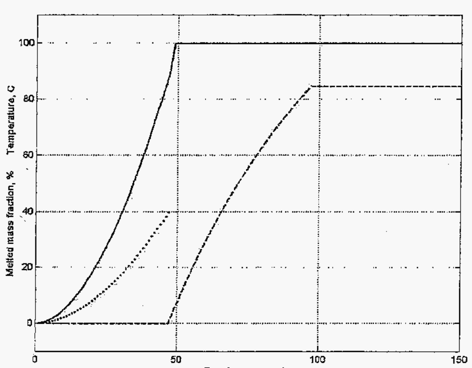

Figure 14. Melted mass fraction and PCM temperature. *Solid line – melted mass fraction in HAB container, dashed line – temperature of PCM and HAB, dotted line – melted mass fraction in inflation system container*

The system ascends to the crossover altitude 15 km in 52 min (99 min after entry). At this altitude the bellows expands to full length (8.6 m), the HAB container opens and the HAB is deployed. By this time all PCM inside the HAB container has been melted and heated further to 84 C. The PCM is released when container opens.

The system has positive free lift and continues to ascend. Also after the HAB deployment the valve connecting bellows with top fitting of the HAB opens and HAB begins to be filled with gas venting from the bellows. At altitude 31 km when most of gas is inside the HAB while gas remaining inside the bellows still provides positive free lift for the bellows itself, the bellows is separated from the HAB. Both vehicles (bellows and HAB with ascend canister and HAB container) continue to rise, bellows moving initially faster than HAB (Figure 13). Horizontal separation between them increases due to windshear. By t=161 min the bellows ascends to its cruise altitude of 34 km. The HAB reaches its ceiling of 58 km in 220 min.

In this example our aim was to illustrate system behavior. Further trade studies are required for optimization.

VII. Return to Venus. VALOR Superpressure Balloon

The last probe mission to Venus that also included first (and only) planetary balloons was 20 years old Soviet-French-US VEGA [6,7] The last American Venus probes were at Venus 30 years ago. Lost capabilities in Venus entry system require re-development and re-qualification of the thermal protection system and some other elements. Even after that a flight validation would be required before any high-cost mission might be selected. VALOR Venus balloon mission proposed in 2004 for Discovery program, besides its high scientific value, presents a low-cost opportunity for development and flight validation of key "return-to-Venus" technologies. Main science objective of VALOR is to resolve fundamental questions of Venus evolution by accurate measurements of composition of Venus atmosphere, first of all noble gases.

VALOR (Venus Atmospheric Long-duration Observatories for in-situ Research) includes two 5.4-m diameter spherical superpressure balloons carrying payload primarily consisted of GCMS (gas chromatograph and mass-spectrometer) and atmospheric structure instrument. Precise radio tracking by VLBA (Very-Long Base Array) and Doppler will yield Venus winds. Being resemble VEGA balloons [6,7], VALOR carries 6 times heavier payload, transmits ~100 times more data and lasts 15 times longer than her VEGA predecessor. It would be first American aerial planetary mission. As VEGA VALOR balloons will fly at 55 km altitude – almost in ideal environment of temperature (20 C) and pressure (0.5 bar). Main challenges are protection from sulfuric acid, large superpressure cycling (~100 mbar) when balloon circumnavigates Venus in convection layer and strict requirement on leakage.

Though VEGA balloon experience used heavily in the VALOR proposal, VEGA-type balloon (made of Teflon fabric coated with Teflon) will be subjected to inelastic expansion and is too permeable to survive even one tour around the planet. Another heritage is taken from the terrestrial manned ATMOSAT balloon [8]. The 10-m spherical Atmosat balloon was made of Kevlar fabric laminated with aluminized Mylar and carried payload ~400 kg in the lower atmosphere. The Atmosat balloon past all development and qualification phases and performed several manned flight with maximum duration 36 hours.

To address challenges with minimum risk, the VALOR balloon was designed with safety factor 5 over maximum stress that would be experienced in the most adverse combination of atmospheric environment during updrafts on the day side of Venus. VALOR balloon has single shell made of composite material. Strength element is Vectran fabric that demonstrated excellent performance in airbags used in Mars Pathfinder and Mars Rover missions. The fabric is coated with polyurethane from inside; polyurethane used for seaming and provides first stage of gas retention. Metalized Mylar laminated on the outside of fabric is virtually impermeable and is designed to retain buoyant gas for more than 30 days. The outer layer is made of silverized Teflon film (silver inside). Teflon protects Mylar and Vectran from sulfuric acid while silver layer gives good combination of optical and infrared properties. Use of proven design and combination of flight validated component materials ensures low-risk implementation.

Similar to VEGA balloons the VALOR balloons will be aerially deployed from the aeroshell. All deployment and inflation sequence will be end-to-end tested in the helicopter drop tests. Successful aerial deployment and inflation of much weker Mylar balloon has been demonstrated in 1998 helicopter drop tests [9]. In the last year we made significant progress in fabrication and tests of materials and hope that a full scale prototype be built later this year.

VIII. Conclusions

Dual-balloon system is the first real approach that will enable VISE and VESSR missions. It implements on all existing materials and technology, and can be simulated in well-known Venus environment. Smaller precursor mission like VALOR will validate re-developed Venus entry probe technologies. By itself the metal bellows and can be designed to fly in any altitudes from near the surface to 15-20 km while Kapton film balloons – from 15-20 t0 50 km. Addition of VALOR-type balloons and polyethylene near zero-pressure balloons will open all range of altitudes from surface to 75-80 km for balloon missions, enabling multi-balloon mission from the Venus "White paper" [10]

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